Strong cloud-circulation coupling explains weak trade cumulus feedback

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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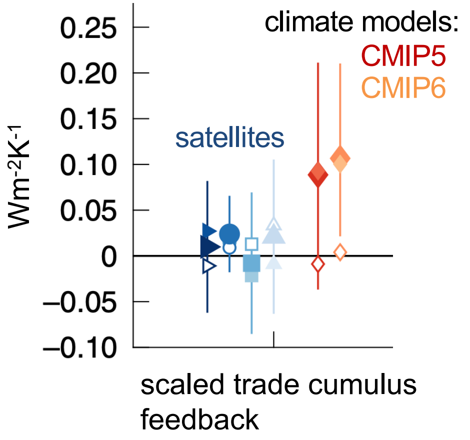
> the trade-cumulus cloud feedback has remained a major source of uncertainty for climate sensitivity *(Bony and Dufresne 2005, Vial et al. 2013, Myers et al. 2021)*

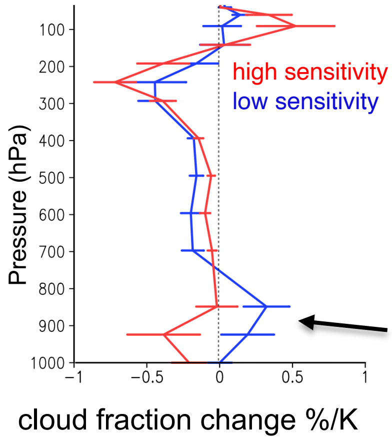
> while many climate models exhibit strong trade cumulus feedbacks, satellite-derived constraints from observed natural variability *(Myers et al. 2021, Cesana and del Genio 2021)* & large-eddy simulations *(Vogel et al. 2016, Radtke et al. 2021)* suggest a rather weak feedback

> In climate models, trade cumulus feedbacks are governed by changes in cloud fraction near cloud base *(Vial et al. 2016, Brient et al. 2016)*

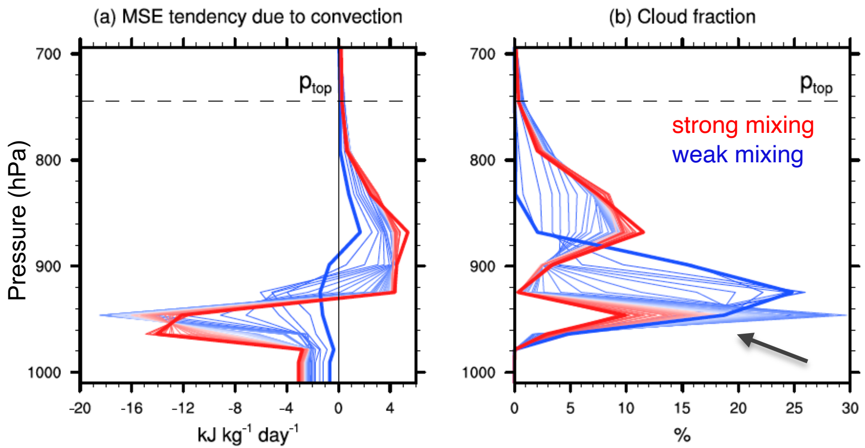
> high sensitivity models suggest a **desiccation of the lower cloud layer with increasing lower-tropospheric mixing** *(Vial et al. 2016, Sherwood et al. 2014)*



(Myers et al. 2021)



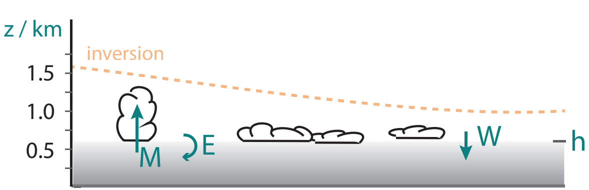
(Brient et al. 2016)



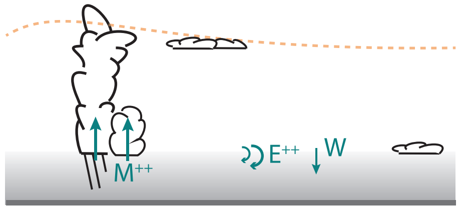
(Vial et al. 2016)

Mixing-desiccation mechanism – *a hypothesis for a strongly positive trade cumulus feedback*

Base state



a Mixing-desiccation mechanism (β<0)



h: sub-cloud layer top
M: mass flux
E: entrainment rate
W: mesoscale vertical velocity
C: cloud-base cloud fraction
R: mean relative humidity

$$\frac{Dh}{Dt} = E + W - M$$

- enhanced moisture transport by convection compensated by down-ward mixing of drier air & evaporation of clouds near cloud base.

→ $C \propto R \propto M^{\beta}$, with $\beta < 0$

- consistent with high-sensitivity climate models & idealized large-eddy simulations of non-precipitating trade cumuli *(Sherwood et al. 2014, Rieck et al. 2012)*

but.....

- $M_{act} = Cac_t\, wac_t$, mostly governed by area fraction of active clouds C_{act} (~50% of total C)

  → $\beta > 0$
- substantial variability in W observed in the trades *(Bony & Stevens 2019, George et al. 2021)*
- never tested with observations

(Bony et al. 2017, Stevens et al. 2021)

Mixing-desiccation mechanism – *a hypothesis for a strongly positive trade cumulus feedback*

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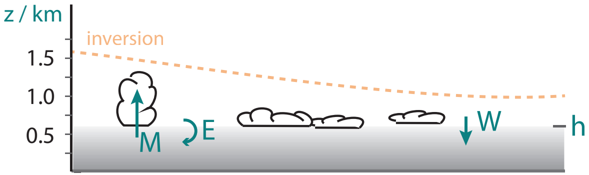

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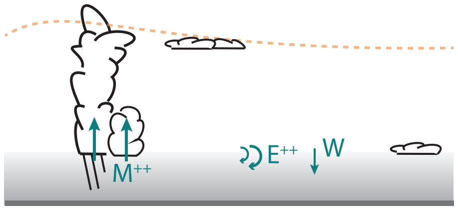

- enhanced moisture transport by convection compensated by downward mixing of drier air & evaporation of clouds near cloud base.

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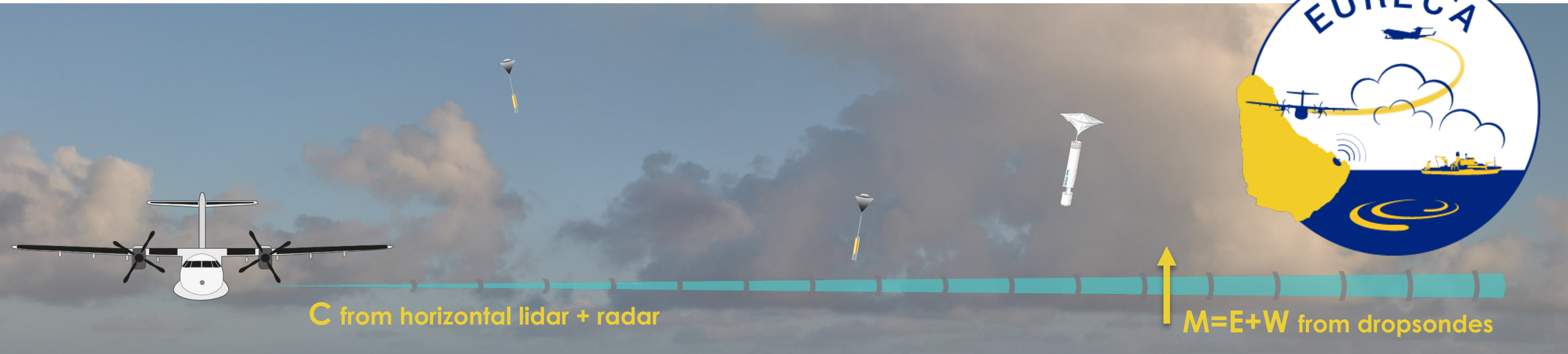
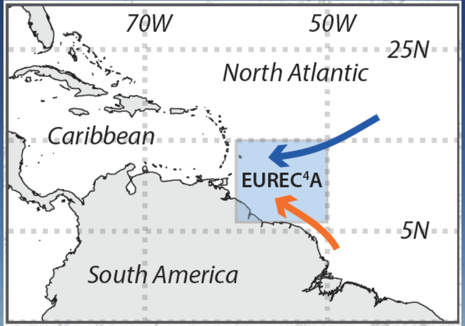
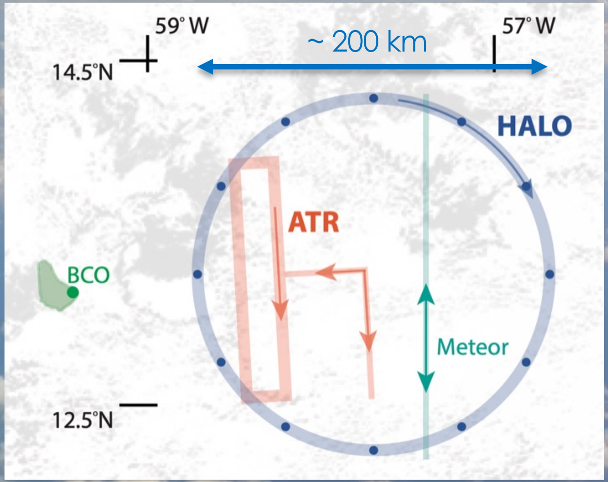


EUREC^{4}A field campaign

(Bony et al. 2017, Stevens et al. 2021)

- Jan-Feb 2020
- 4 aircraft & ships, drones, BCO...
- goal: test mixing-desiccation hypothesis
- Clouds @Barbados representative for entire trade-wind belt *(Medeiros & Nuijens 2016)*





mass flux estimation from dropsonde measurements

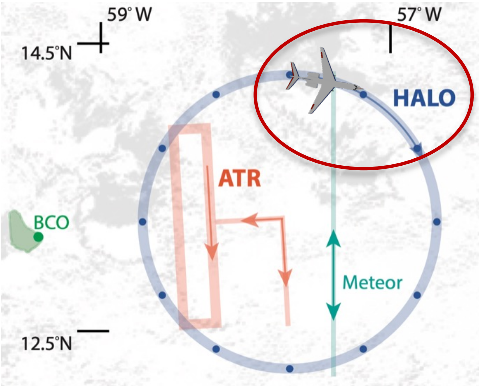
Mass flux estimation using EUREC⁴A dropsondes

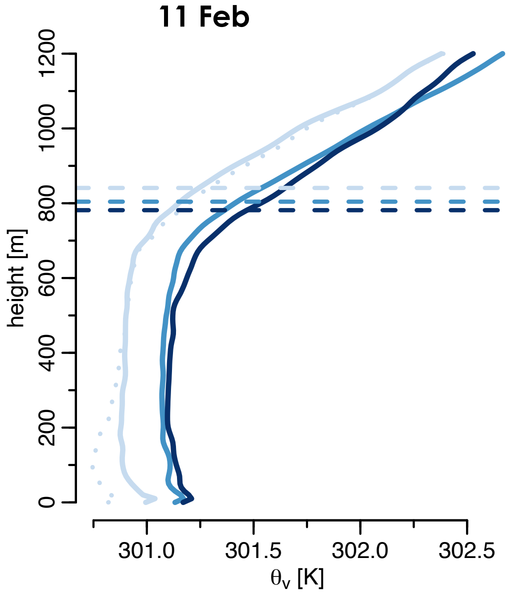
$$M = E + W - \cancel{\frac{\partial h}{\partial t} - v_h \cdot \nabla h}$$

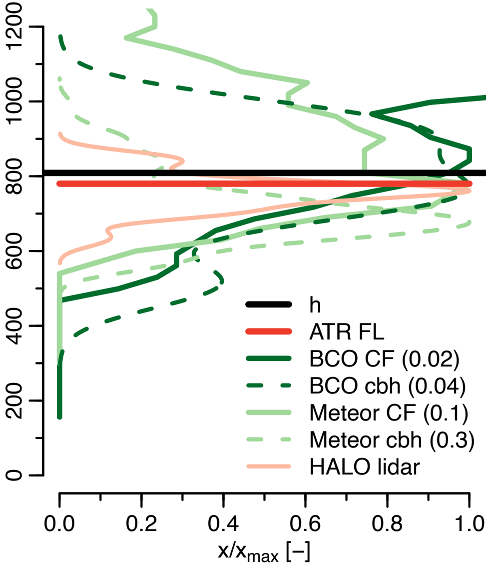
~ $M_{act} = a_{act}\, w_{act}$ *(Vogel et al. 2020)*

> sub-cloud layer top *h*

- target: max. cloud-base cloud fraction level
- definition: $\theta_v(h) \geq \overline{\theta_v} + \epsilon$, with $\epsilon = 0.2K$







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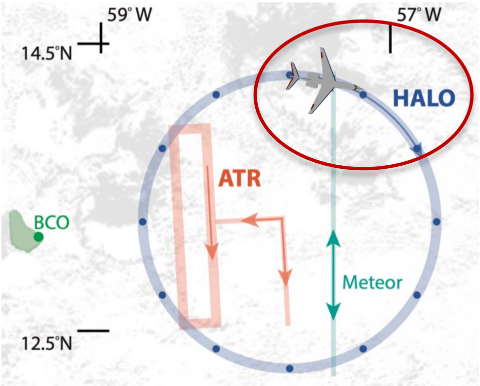


> sub-cloud layer top *h*

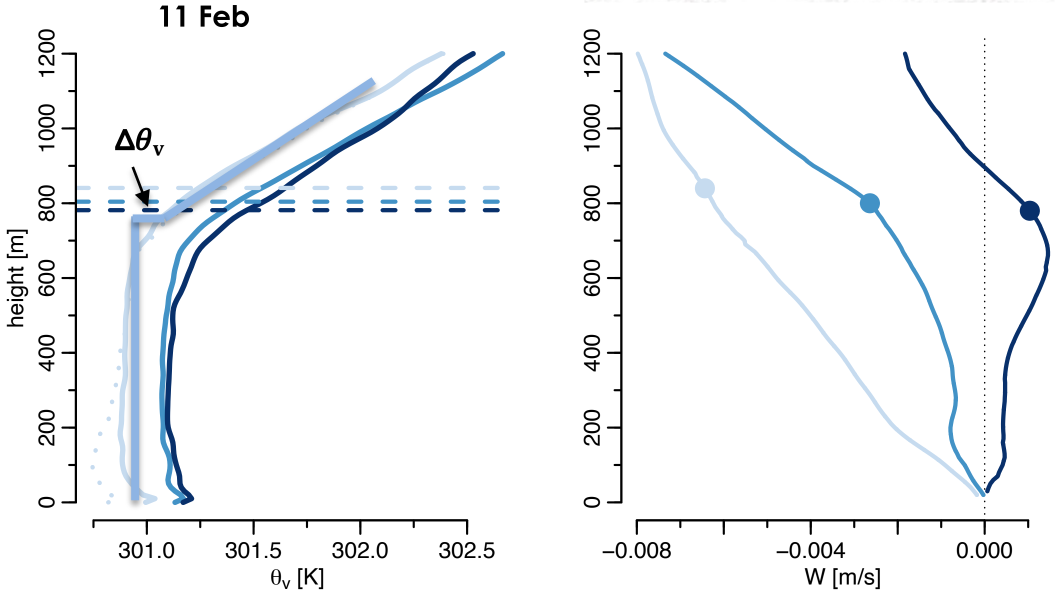
- target: max. cloud-base cloud fraction level
- definition: $\theta_v(h) \geq \overline{\theta_v} + \epsilon$, with $\epsilon = 0.2K$

> entrainment rate *E*:

$E = \frac{A_e \overline{w'\theta_v'}|_s}{\Delta\theta_v}$, with A_e = 0.43 *(Albright et al., 2022)*

> mesoscale vertical velocity *W* at *h*:
from regression method *(Bony & Stevens 2019)*

>> target scale: 3-circle averages (~3h, 200 km)

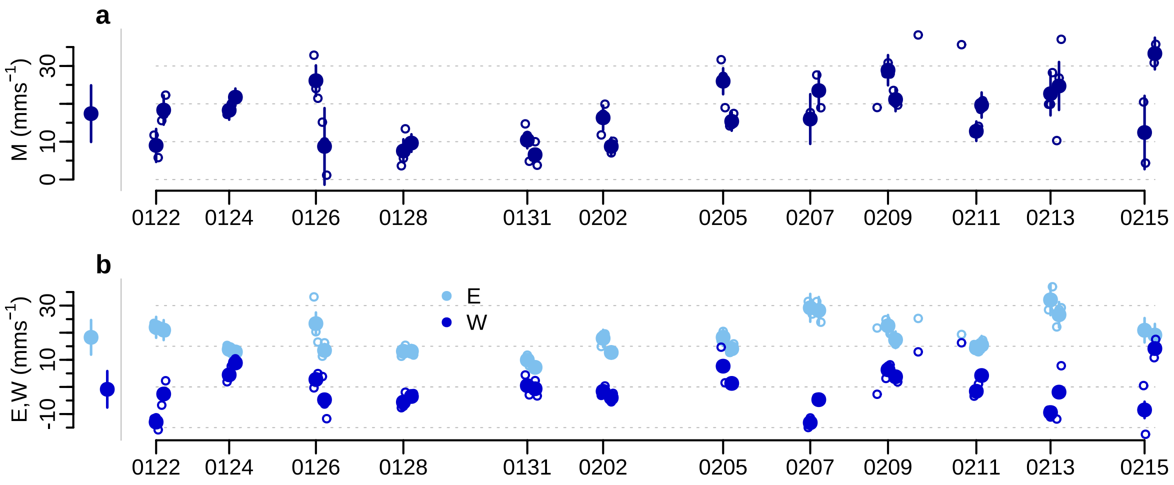


First observations of convective mixing at the mesoscale

- M and E robust to changes in estimation procedure and consistent with independent data

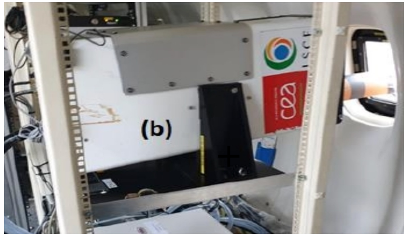
- on average, M~E

- but on shorter timescales, E & W contribute almost equally to variability in M



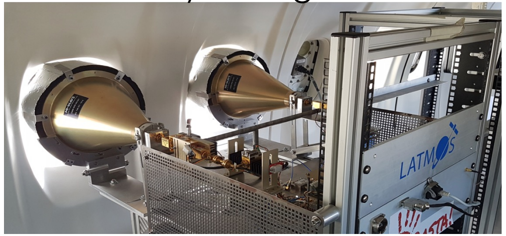
Cloud-base cloud fraction

horizontally-staring 355nm ALIAS lidar

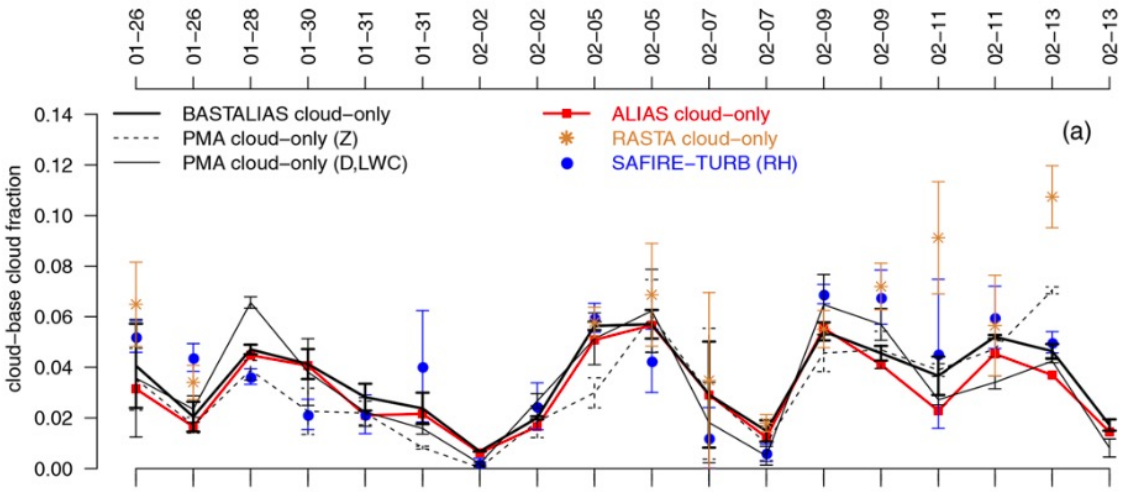


(Chazette et al. 2020)

horizontally-staring 94GHz BASTA Doppler radar



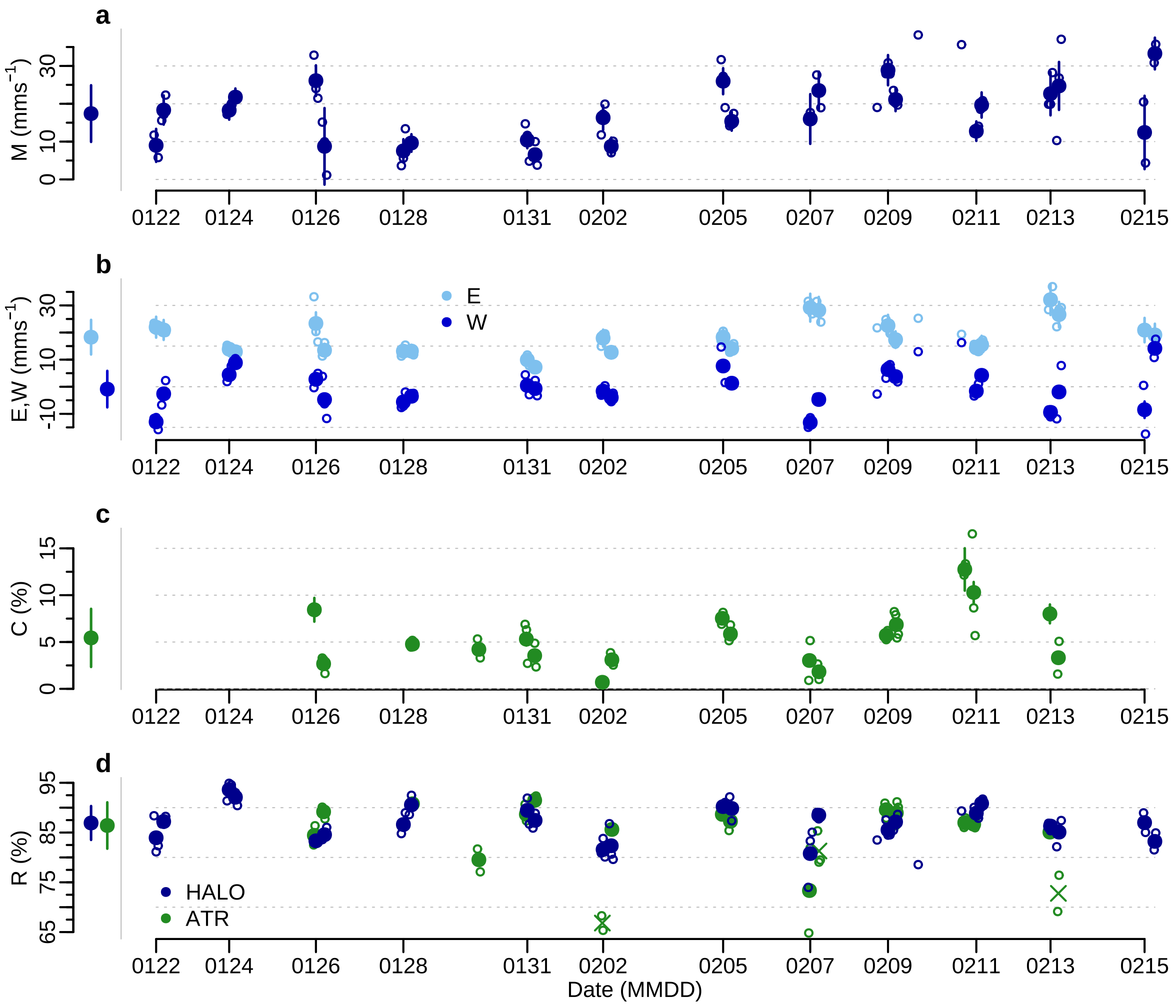
(Delanoëet al. 2016)



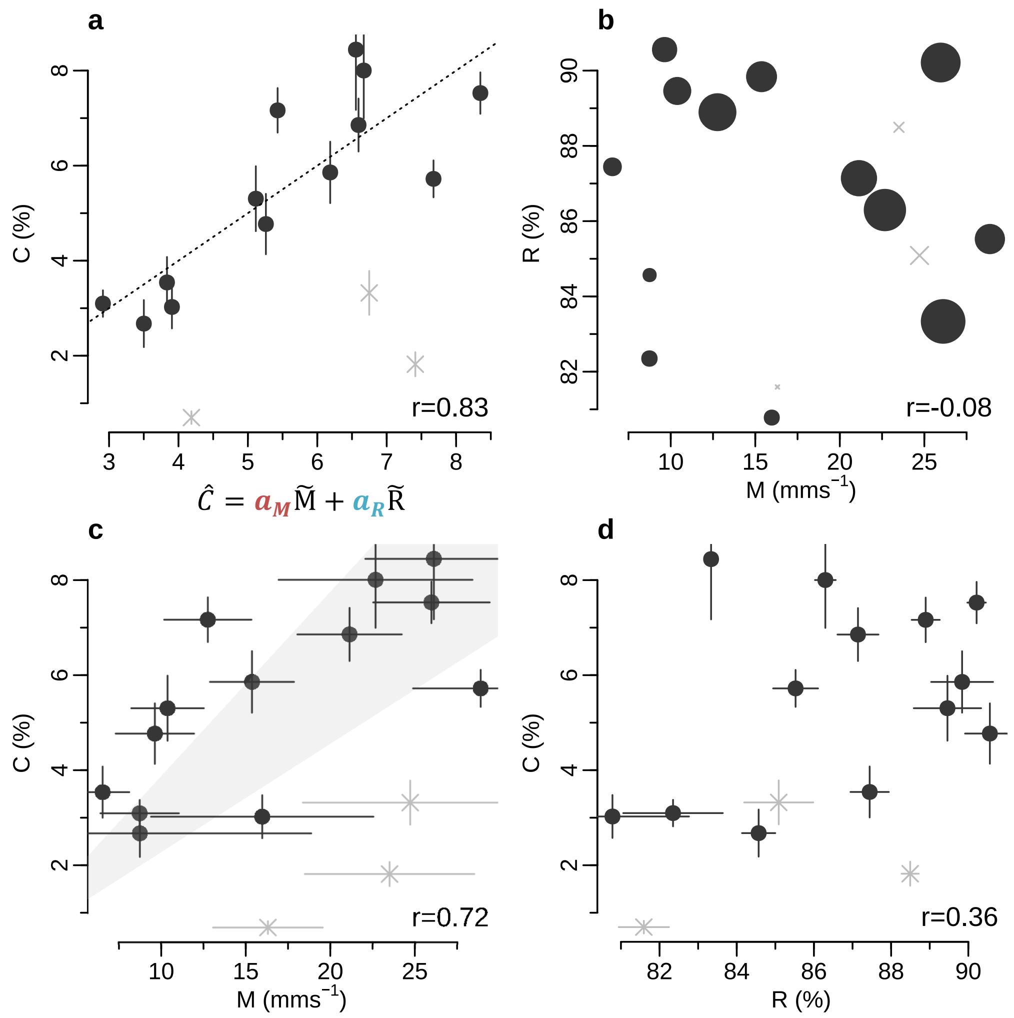
very good agreement among different instruments *(Bony et al. 2022)*

First observations of M, C and RH co-variations

- C is both small and highly variable
- R is robustly around 86%
- 3 circle-sets with inconsistent sampling neglected



Do we find evidence for the mixing-desiccation mechanism in the EUREC^{4}A data?



M: mass flux
E: entrainment rate
W: mesoscale vertical velocity
C: cloud-base cloud fraction
R: mean relative humidity

W & E contribute equally to variability in M, but have opposing relations to R

→ negligible desiccation effect of M!

M alone explains 50% of C variability

dynamical control through M overwhelms thermodynamic control through R → $a_M/a_R \sim 1.8$

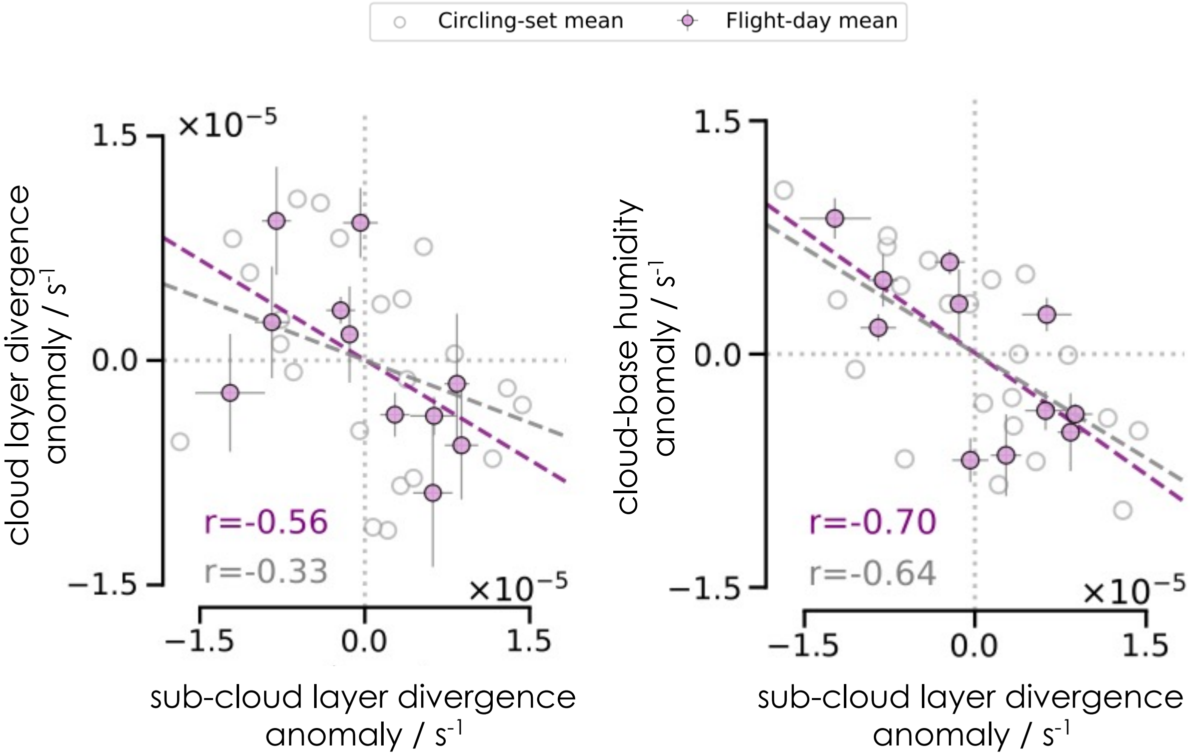
EUREC^{4}A data refute mixing-desiccation mechanism

Ubiquity of SMOCS* and their influence on moisture variance in the trades

(George et al. 2022, in review)

*Shallow Mesoscale Overturning Circulations

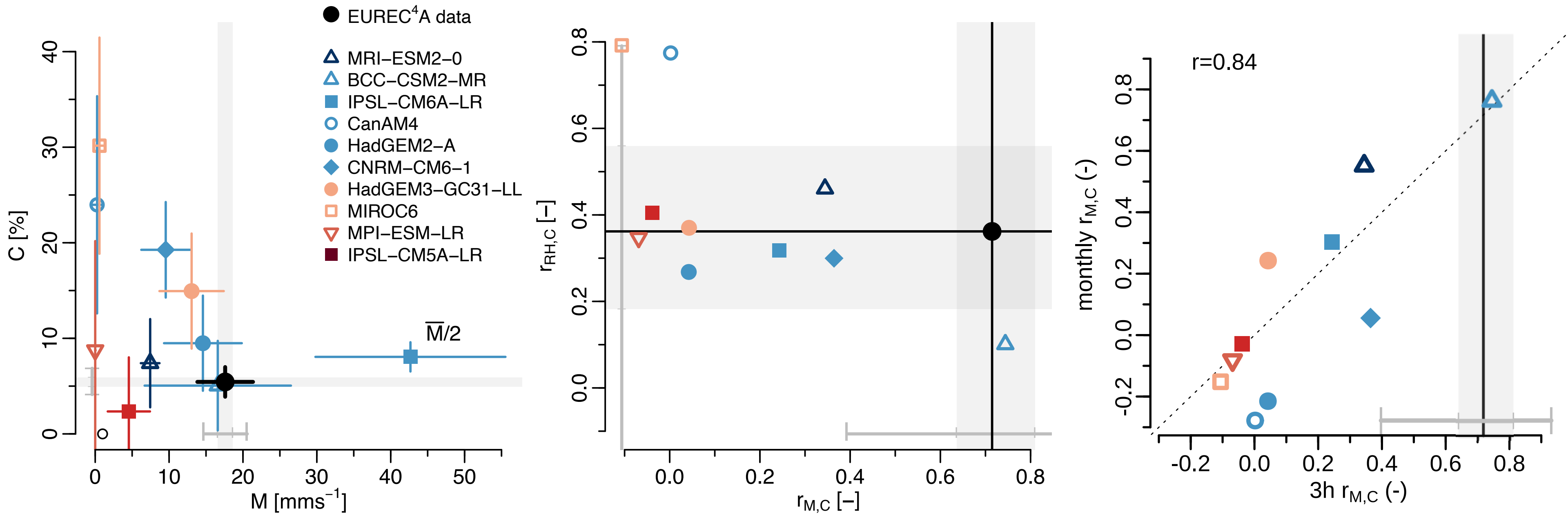
- anti-correlation between divergence in the sub-cloud and cloud layers
- Sub-cloud convergence correlated with moister sub-cloud and cloud-base layers
- ERA5: SMOCs are elongated features of ~100-200 km and cover ~58% of domain



- 4 CMIP5 and 6 CMIP6 models (Taylor et al. 2012, Eyring et al. 2016)
- AMIP 1979-2008 & AMIP+4K (uniform warming)
- Winter months (DJFM)
- subhourly output at selected sites from CFMIP (Webb et al. 2017): BCO, BOMEX, EUREC^{4}A, NTAS
- monthly outputs over 60W-44W, 11N-16N

How consistent is the present generation of climate models with our observations?

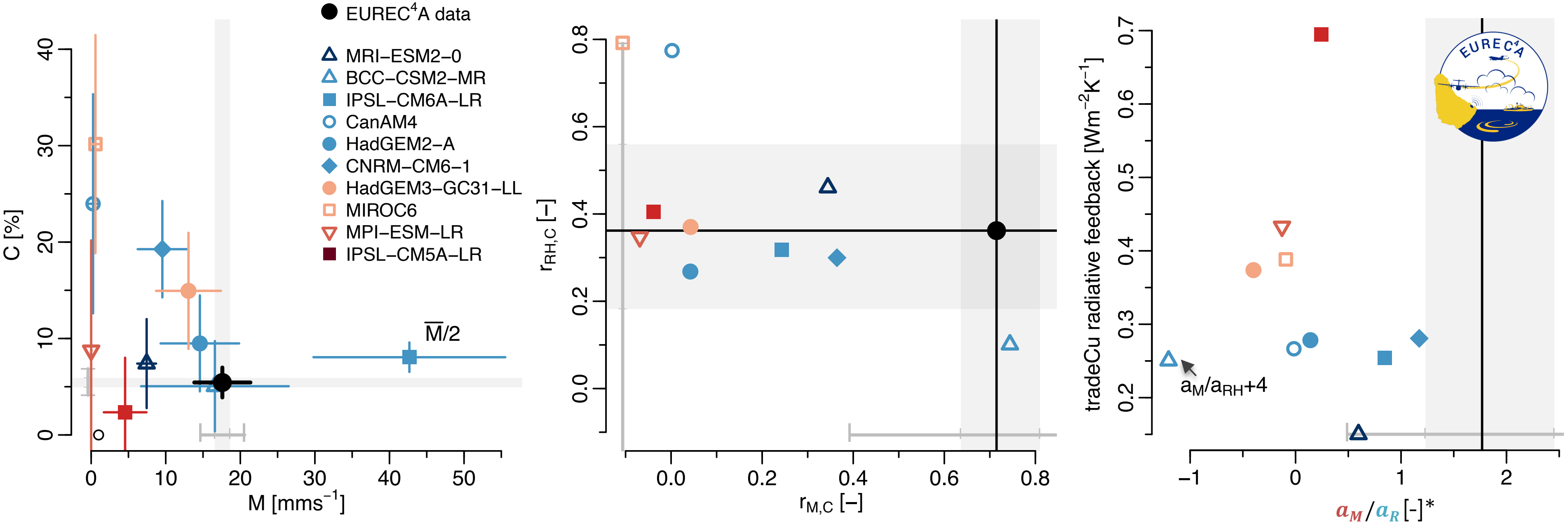
Models underestimate strong cloud-circulation coupling



Magnitude, variability, and coupling of M, C and R in CFMIP models differs drastically from EUREC^{4}A data

Underlying fast physical processes that couple M, R and C in the models are largely time-scale invariant

Process-based constraints render strongly positive trade cumulus feedbacks implausible



Magnitude, variability, and coupling of M, C and R in CFMIP models differs drastically from EUREC⁴A data

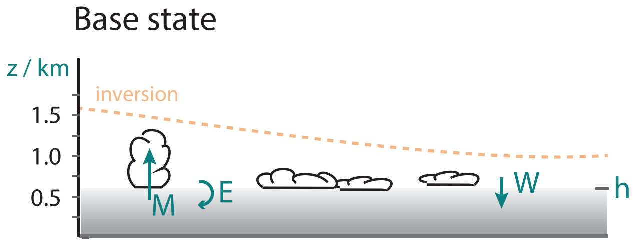
Underlying fast physical processes that couple M, R and C in the models are largely time-scale invariant

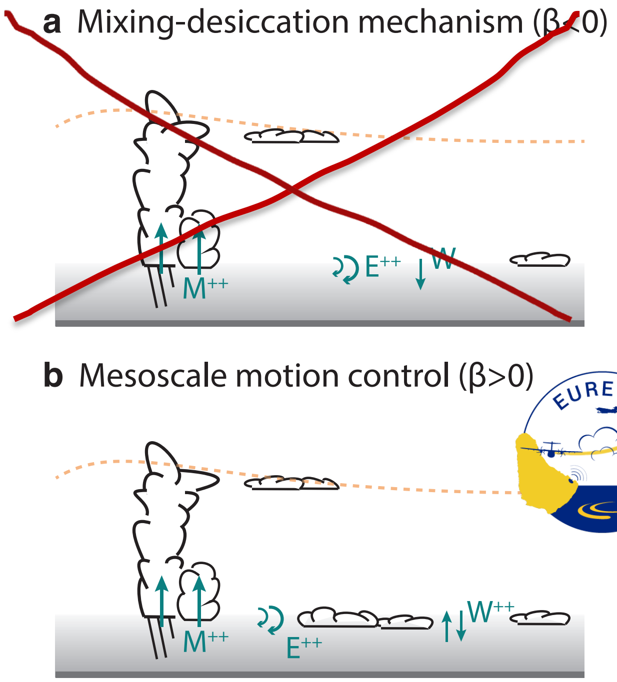
Models with largest positive feedback represent refuted mixing-desiccation mechanism and particularly exaggerate variability of C and coupling of C to R instead of M (small a_M/a_R)

*a_M/a_R from $\hat{C} = a_M\tilde{M} + a_R\tilde{R}$

conclusions

Conclusions





EUREC^{4}A emphasizes dynamic factors—convective and mesoscale motions—as dominant controls of cloudiness, rather than thermodynamic factors related to the mixing-desiccation mechanism.

By refuting the mixing-desiccation mechanism, the EUREC^{4}A data...

... refute an important mechanism for a strongly positive trade cumulus feedback and thus a critical line of evidence for a large climate sensitivity *(Stevens et al. 2016)*

... render climate models with strong positive feedbacks implausible

... both support *(Myers et al. 2021, Vogel et al. 2016)* and explain at the process scale a weak trade cumulus feedback

paper accepted in *Nature*, preprint: https://doi.org/10.1002/essoar.10512547.1